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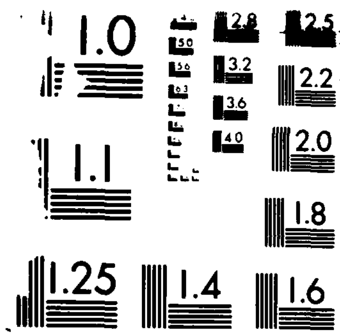

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Elltec Engineering Inc.

Multiple Scattering Effects of
an Ensemble of Irregularly Shaped Particles

Final Report

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October 1, 1986

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This report summarizes the result of the research carried out at EMtec Engineering, Inc., Los Angeles, under contract DAAG29-84-C-0019 with the Army Research Office. This research explored the fundamental issues associated with wave propagation in a medium consisting of an ensemble of nonspherical particles for which the multiple scattering effects are important. The approach is based on the vector transport theory, which includes the depolarization effects. Specifically, we dealt with beam wave propagation through an ensemble of uniformly distributed and non-uniformly distributed nonspherical particles. Also listed in this report are several future research areas.

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Abstract

This report summarizes the result of the research carried out at EMtec Engineering, Inc., Los Angeles, under contract DAAG29-84-C-0019 with the Army Research Office. This research explored the fundamental issues associated with wave propagation in a medium consisting of an ensemble of nonspherical particles for which the multiple scattering effects are important. The approach is based on the vector transport theory, which includes the depolarization effects. Specifically, we dealt with beam wave propagation through an ensemble of uniformly distributed and non-uniformly distributed nonspherical particles. Also listed in this report are several future research areas.

Table of Contents

I. Introduction

This is a final report on a study sponsored by the Army Research Office (DAAG29-84-C-0019) from August 1, 1984 through July 31, 1986. The principal objective of this research was to explore the fundamental issues associated with wave propagation in a medium consisting of an ensemble of irregularly shaped particles. The approach based on the vector transport theory which includes the depolarization effects was used. Three projects were performed: (a) Calculation of the backscattered and forward-scattered incoherent specific intensities caused by the multiple scattering effects from nonspherical particles, (b) Beam wave propagation through an ensemble of nonspherical particles, (c) Wave propagation in a medium with non-uniform density distribution of particles. This final report gives a summary of our accomplishments during this phase of the research program.

II. Summary of Accomplishments

Results of our investigation are summarized in the following:

(a) Calculation of the backscattered and forward-scattered incoherent specific intensities caused by the multiple scattering effects from non-spherical particles.

It is important to distinguish the vector radiative transfer equation which is capable of including the polarization effects, from the scalar radiative transfer equation. Our formulation for the incoherent intensities is based on the equation of transfer for the Stokes' parameters, while the formulation for the coherent intensities is based on the classical approach of van de Hulst. A linearly polarized wave is assumed to be obliquely incident upon a plane-parallel medium containing the ensemble of uniformly distributed identical particles. It is assumed that every particle is a spheroid whose symmetry axis is normal to the slab. We aim at computing the backscattered and forward-scattered incoherent field that is generated within the slab, in terms of its Stokes' vector. Our starting-point is the integro-differential equation of radiative transfer. This formulation provides the incoherent Stokes' vector for a given normal or oblique illumination as a function of the scattering amplitudes of a single particle. Both attenuation and multiple scattering are taken into account. The analysis is based upon the Fourier expansion of this equation of transfer. Because of the specific symmetry and orientation of the particles, the Fourier components of the Stokes' vector are independent of one another. Such a decoupling enables us to determine a given component by solving the separate equation of transfer that it will satisfy. After an estimate of the integral terms by Gauss' quadrature, the component's values on a net of discrete backward and forward directions are solutions of a system of first-order differential equations with constant coefficients and are computed by an eigenvalues-eigenvector technique. A partial sum of the Fourier series composed of such components represents the incoherent Stokes' vector; in the case of normal incidence, only two such components are different from zero (order 0 and 2).

The behavior of the incoherent field is thereby investigated for low-loss particles (ice) and high-loss particles (smoke) illuminated by x-polarized waves under typical incidences. Patterns of the x-polarized (co-polarized) and y-polarized (cross-polarized) foward-scattered as well as backscattered incoherent intensities versus the direction of observation are computed. These results enable us to examine the convergence of the process and the influence of the particles' geometry and distribution. The consequences of the low- or high-losses are emphasized. Comparisons with results obtained by a first-order scattering theory are also carried out. Initial indication is that excellent qualitative as well as quantitative agreement was found for low particle density - small optical depth medium and good qualitative (but not so good quantitative) agreement was also apparent for higher particle density - larger optical depth medium.

Results for the first-order multiple scattering theory and those for the forward-scattered incoherent intensities for a slab of nonspherical particles have been published in Applied Optics and Radio Science, respectively. Results for the backscattered incoherent intensities will be published in Radio Science.

(b) Beam wave propagation through an ensemble of spherical or nonspherical particles.

In many practical situations where the transmitter and the receiver are located sufficiently close so that the usual plane wave incidence assumption may not be valid, the beam wave characteristics of the incident wave must be taken into consideration. There are two ways of solving this problem. The first way, the exact way, is based on the full vector radiative transfer theory and the expansion of the incident beam wave in plane wave spectrum. Solution of the vector radiative transfer equation starts with the expansion of the equation in Fourier series ϕ. The integral with respect to μ is converted to a series representation by the Gauss' quadature formula. The resultant set of coupled linear first-order equations are then solved by the eigenvalue-eigenfunction technique with the given boundary conditions. The second way, the approximate way, uses a perturbation technique on the transfer equation. The result, called the first-order solution, is a set of analytic expressions for the incoherent intensities. We have progressed in both of these directions. The attractiveness of the first-order approach is in its simplicity and clarity and the ease of obtaining numerical results while the exact approach, although very complicated, provides accurate results which can be used as reference or check points for the first-order or other approximate approaches. The exact results may also provide regions of validity for the approximate first order expressions. It is noted that because of complexity of the exact approach and the many resultant numerical difficulties associated with large, ill-conditioned matrices, extreme care must be taken in performing the calculations. We have successfully treated the problem of a slab of uniformly distributed identical oblate or prolate spheroidal particles with their symmetry axis aligned along the normal direction of the slab. Different sizes, shapes, and densities of the particles as well as different incident angles for the plane wave were considered. This is the first time that such a calculation, taking into consideration the complete polarization effects, has been carried out for an ensemble of the nonspherical particles.

The first-order results, as well as the results from the exact vector radiative transfer approach, are being prepared for publication in Applied Optics.

(c) Wave propagation in a medium with non-uniform density distribution of particles.

For most realistic situations, particles in smoke or clouds are usually inhomogeneously distributed. We plan to attack this problem by solving the vector radiative transfer equation for inhomogeneous medium. The initial step is to obtain the solution based on first-order scattering. Results of this work were reported in the 1986 CRDEC Scientific Conference on Obscuration and Aerosol Research. It is known that the effects of inhomogeneities on the wave fluctuations are not significant for turbulent medium because the turbulent scale is normally much greater than a wavelength and the wave is mostly scattered within very small forward angles and the difference between the extended medium and the thin screen is relatively small. The situation is very much different for discrete scatterers whose sizes are often comparable to wavelengths. In this case, the scattering takes place over a wide angle and wave characteristics are greatly affected by the location of the random medium and the inhomogeneities. We are now concentrating our effort to investigate the effects of inhomogeneities in the line-of-sight, as well as transverse inhomogenities.

Results of this investigation are being prepared for publication in Radio Science.

III. Future Research Areas

Having developed our capability in solving the vector transport equation for non-spherical particles, we are now in a position to expand our horizon to perform research in the following areas:

(1) Scattering in inhomogeneous random medium

(2) Study of wave propagation in high density medium using the modified radiative transfer theory

(3) Pulse propagation in a random medium

IV. Listings of Papers and Presentations

The following is a list of papers and presentations by our group during the current ARO research program.

(a) "Multiple scattering calculations for non-spherical particles based on the vector radiative transfer theory", Radio Science 19, pp. 1356-1366, Sept-Oct. (1984).

(b) "First-order multiple scattering theory for nonspherical particles", Appl. Opt. 23, pp. 4132-4139, Nov. (1984).

(c) "Backscattered incoherent intensities for an ensemble of nonspherical particles--vector radiative transfer approach", presented at the 1984 CLS Scientific Conf. on Obscuration and Aerosol Research, Aberdeen Proving Ground, Maryland; being prepared for publication in Radio Science.

(d) "Multiple scattering of beam waves by an ensemble of nonspherical particles" presented at the 1985 CLS Scientific Conf. on Obscuration and Aerosol Research, Aberdeen Proving Ground, Maryland; being prepared for publication in Appl. Opt.

(e) "Beam wave scattering by inhomogeneously distributed particles" presented at the 1986 CLS Scientific Conference on Obscuration an Aerosol Research, Aberdeen Proving Ground, Maryland; being prepared for publication in Radio Science.

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